dSPACE based direct-driven permanent magnet synchronous wind power system modeling and simulation

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ABSTRACT

When the wind speed is below rated value, the efficiency of captured wind energy must be maximized and the mechanical oscillation is guaranteed to be small. This essay deals with these problems, not only describes the advantages of the direct-driven permanent magnet synchronous wind power system, but also introduces two frequency loop model based on frequency separation principle, and suggests LPV model and LPV control method for high-frequency part of the system, the output of the high-frequency part is used to compensate the mechanical torque. The mathematical model is built with MATLAB, and the online test is carried out by dSPACE. The simulation results show that the controller reduces mechanical oscillation effectively, and enhances the system reliability.

Keywords: LPV, direct-driven permanent magnet synchronous wind turbine, Wind Power Conversion System, dSPACE

1. INTRODUCTION

Wind power is a clean renewable resource. After 20 years development, the cost of wind power generation is greatly reduced, and the system performance is gradually improved. Wind power has become an important strategy for national economic development (Akpinar, E.K and Akpinar, S 2006; Yazhou Lei and Gordon Lightbody 2005).

The wind power system mostly adopts DFIG at present, and it has gearbox between generator and wind turbine, gearbox not only consumes a part of energy, but also has big noises, high failure rate and high maintenance costs. Permanent magnet synchronous generator is a newer type motor without brush and commutator, so it has big power factor. Direct-driven permanent magnet synchronous wind turbine has no gearbox, namely that the wind turbine and generator is connected directly, so it can promote the efficiency, improve the reliability of the system and decrease failure rate and maintenance costs.

In the wind power system, the control objective under rated wind speed is to maximize the efficiency of captured wind energy, but the traditional control methods usually cause high mechanical oscillation. Since the wind energy conversion system (WECS) is a typical strong non-linear system, many control means need to transform non-linear model to linear model, such as PI and PID control(Tapia A, Tapia G and Ostolaza Jx 2003), and some advanced control ways, like LQ and LQG control(Muhando Be, Senjyu T and Urasaki N 2007), however, the robustness of all these control methods is low, this becomes an applying restrictions for these control methods. The randomness of wind often results in low resolution linear model, document(Shamma,J. and Athans,H. 1991) proposed LPV(Linear Parameter Varying) control which can solve above problems efficiently.

Firstly, this paper introduces double frequency loop model of the system(Inlian Munteanu, Nicolaos Antonio Cutululis and Antoneta Iuliana Bratcu 2005;2008), and then the low-frequency part uses PI control, and build LPV model for the high-frequency part, based on this model, adopts LPV control method, it can promote the accuracy of the model, also, can maximize the efficiency of captured wind energy and restrain oscillation. This paper built simulation model based on MATLAB, then loaded onto dSPACE to make on-line experiment, the experiment result shows LPV control can improve the performance of the system, and it proved the feasibility and superiority of the control method.

2. WIND ENERGY CONVERSION SYSTEM MODEL

The dynamic process of generator electromagnetic response is ignored in this paper, since the electromagnetic time constant is much smaller than the mechanical time constant. The system model established in this paper is ideal. The structure of variable speed constant frequency wind power energy conversion system is shown in Figure 1.



Figure 1: Structure of Variable Speed Constant Frequency WECS

In Figure 1, the wind turbine and generator are connected directly, Drive Train represents the shaft, and there is no gearbox between them. For this reason, they have the same speed Ω_i .

2.1. Wind Speed Model

Wind speed v(t) which is a non-statistical random process is decomposed into two components in many references (Bianchi F, De Battista H and Mantz RJ 2006; Nichita C, Luca D, Dakyo B and Ceang E 2002), that is

$$v(t) = \overline{v}(t) + \Delta v(t) \tag{1}$$

Where $\overline{v}(t)$ is low-frequency component, which describes long-time scale and low-frequency changes, it is usual to assume to be a Weibull distribution; and $\Delta v(t)$ is high-frequency component, and the highfrequency part $\Delta v(t)$ is made up of Gaussian white noise e(t) as a disturbance signal composed of a firstorder filter.

$$\Delta \dot{v}(t) = -\frac{1}{T_w} \Delta v(t) + \frac{1}{T_w} e(t)$$
⁽²⁾

Where T_{w} is the time constant of the filter, and $T_w = L_t / \overline{v}$. L_t is the length of wind speed turbulence.

2.2. Wind Turbine Model

According to the Bates theory, the mechanical power captured by turbine is:

$$P_{wt} = 0.5\pi\rho R^2 C_p(\lambda) v^3 \tag{3}$$

Where ρ is air density, R is the radius of wind turbine, v is wind speed, λ is tip speed ratio, and $\lambda = R \cdot \Omega_1 / v$, Ω_{i} is the angular velocity of wind turbine rotor, $C_{i}(\lambda)$ is the power factor of wind turbine, which is defined as:

$$C_p(\lambda,\beta) = 0.22(\frac{116}{\lambda} - 0.4\beta - 5)e^{\frac{-12.5}{\lambda}}$$

Where β is the pitch angle of variable-pitch control, for the fixed-pitch control, $\beta = 0$.

The torque of wind turbine is:

$$\Gamma_{wt} = \frac{P_{wt}}{\Omega_l} = 0.5\pi\rho R^3 v^2 C_{\Gamma} \left(\lambda\right) \tag{4}$$

Where $C_{\Gamma}(\lambda)$ is torque coefficient which is defined as $C_{\Gamma}(\lambda) = C_{p}(\lambda)/\lambda$.

2.3. Drive Train Model

Neglecting the transients, the rigid drive train is expressed as:

$$J_{l}\dot{\Omega}_{l} = \Gamma_{wl} - \frac{i}{\eta}\Gamma_{G}$$
⁽⁵⁾

Where J_i is the total inertia of drive train, *i* is the gear box ratio, for the direct-driven case, its value is 1, η is the efficiency of the transmission shaft, Γ_{G} is the electromagnetic torque of the generator. As mentioned above, the formula (4) and (5) constitute the basic lowfrequency model of the wind power conversion system.

2.4. Model of PMSG

To suppose the permanent magnet synchronous motor is ideal, when we analyze its basic electromagnetic relations. So it fulfills:

- 1. Ignore the influence of the core magnetic saturation, excluding the eddy current and hysteresis loss.
- 2. The conductivity of permanent magnetic materials is zero.
- There is no damper winding in rotor. 3.
- The three-phase of stator is symmetrical and 4. the induced EMF (electromotive force) is sinusoidal

The electromagnetic torque of permanent magnet generator in d,q coordinate system is

$$\Gamma_G = p(\Phi_d i_q - \Phi_q i_d) = p[\Phi_m i_q + (L_d - L_q) i_d i_q]$$
(6)

It is assumed that the load of the generator R_l is independent and symmetric three-segment, and the states and input of the system are defined as:

$$\begin{aligned} x &= \begin{bmatrix} x_1(t) & x_2(t) \end{bmatrix}^T \equiv \begin{bmatrix} i_d(t) & i_q(t) \end{bmatrix}^I \\ u &\equiv R. \end{aligned}$$

The state model of the generator can be expressed:

$$\begin{cases} \frac{1}{x} = \begin{bmatrix} \frac{1}{L_d + L_s} (-Rx_1 + p(L_q - L_s)x_2\Omega_l) \\ -\frac{1}{L_q + L_s} (-Rx_2 - p(L_d + L_s)x_1\Omega_h + p\Phi_m\Omega_h) \end{bmatrix} + \\ \begin{bmatrix} -\frac{1}{L_q + L_s} & 0 \\ 0 & -\frac{1}{L_q + L_s} \end{bmatrix} \\ y \equiv \Gamma_{c_1} = p\Phi_{-}x_2 \end{cases}$$
(7)

Where *R* is the stator resistance, L_d and L_q are the inductance of the stator in d,q coordinate system, i_d and i_q are the stator current, L_s is the equivalent inductance of grid and converter, Φ_m is the flux, and is a constant for the permanent material, p is the pole pairs of the generator.

3. LPV CONTROLLER DESIGN

The LPV theory was firstly proposed by Professor Shamma, its dynamic characteristics depend on the adjustable parameters which are measured in real time(Shamma,J. and Athans,H. 1991). Since these parameters can reflect the nonlinearity of the system, LPV system can be applied to describe non-linear system. Design gain scheduling controller using linearization method to make controller gain change with the parameters.

Refer to the references (Inlian Munteanu, Nicolaos Antonio Cutululis and Antoneta Iuliana Bratcu 2005; 2008), the LPV model of the system can be expressed:

$$x(t) = Ax(t) + Bu(t) + Le(t)$$

$$y(t) = Cx(t)$$
(8)

The formula (8) shows that external interference e(t) exists in the LPV model. In order to effectively suppress wind disturbance and improve the system dynamic performance, the controller is designed based on the LPV dynamic model, making the H_{∞} norm of the closed-loop transfer function $T_{ez}(s)$ from the disturbance input e(t) to the control output y(s) less than a given performance index, that is

$$\left\|\boldsymbol{T}_{ez\infty}\left(s\right)\right\|_{\infty} < \gamma_{\infty}$$

then the designed state feedback controller is

$$u(t) = K(\rho(t)) \cdot x(t)$$

the closed-loop system is obtained:

$$\dot{x}(t) = (A(r(t)) + B(r(t))K(r(t)))x(t) + Le(t)$$

$$y(t) = C(\rho(t))x(t)$$
(9)

The affined parameters of this LPV model depend on $\rho(t)$, and the controller matrix is solved according to theorem 1.

Theorem 1(Junling Wang 2008)

For the LPV model described by formula(8) and a given positive constant, if there are continuously differentiable symmetric positive definite matrix $X(\rho(t))$, symmetric positive definite matrix Y, matrix

V and $R(\rho(t))$ satisfying formula(10) for all the parameters, then the parameters of closed-loop (9) are quadratic stability and meet the given H_{∞} performance.

$$\begin{bmatrix} -(V+V^{T}) & * & * & * & * & * \\ M & -X(\rho(t))+Y & * & * & * & * \\ 0 & 0 & -Y & * & * & * \\ L^{T}(\rho(t)) & 0 & 0 & -\gamma_{\infty}I & * & * \\ 0 & C(\rho(t))V & 0 & 0 & -\gamma_{\infty}I & * \\ V^{T} & 0 & 0 & 0 & 0 & -X(\rho(t)) \end{bmatrix} < 0$$
(10)

where

$$M = V^{T} A^{T} (\rho(t)) + R^{T} (\rho(t)) B^{T} (\rho(t)) + X (\rho(t))$$
. If
the inequality (10) has feasible solution, then the state
feedback controller gain matrix which dependent on the
parameters is

$$K(\rho(t)) = R(\rho(t))V^{-1}$$

according to the formula (5),

$$J_T \overline{\Delta \Omega_l} = \overline{\Delta \Gamma_{wt}} - \frac{1}{\eta} \frac{\overline{\Gamma_G}}{\overline{\Gamma_{wt}}} \overline{\Delta \Gamma_G}$$
(11)

Where
$$J_T = J_l \overline{\Omega_l} / \overline{\Gamma_{wt}}$$
, $\overline{\Delta \Omega_l} = \frac{\Delta \Omega_l}{\overline{\Omega_l}}$, $\Delta \Omega_l = \Omega_l - \overline{\Omega_l}$,

 $\overline{\Omega_l}$ is the stable value of the Ω_l , also for the $\frac{1}{\overline{\Omega_l}}$, $\frac{1}{\Delta\Omega_l}$ and $\overline{\Delta\Gamma_{vvl}}$.

According to the high-frequency pulsation wind speed modeling method in the reference [9] and formula (2), there is

$$\frac{\overline{\Delta v}}{\overline{\Delta v}} = \frac{1}{T_w} \left(e - \overline{\Delta v} \right) \tag{12}$$

and according to formula (4) and low-frequency submodel,

$$\overline{\Delta\Gamma_{wt}} = \gamma \cdot \overline{\Delta\Omega_l} + (2 - \gamma)\overline{\Delta\nu}$$
(13)

 $\gamma\,$ depends on the low-frequency operating point of the

system, its value is $\gamma = \frac{\overline{\lambda} C'_{p}(\overline{\lambda})}{C_{p}(\overline{\lambda})} - 1$, and

$$C'_{p}\left(\overline{\lambda}\right) = \frac{dC_{p}\left(\lambda\right)}{d\lambda}.$$

Put the formula (11) and (12) into (13), there is

$$\frac{\dot{\Delta}\Gamma_{wt}}{\Delta\Gamma_{wt}}(t) = \left(\frac{\gamma}{J_T} - \frac{1}{T_w}\right)\overline{\Delta}\Gamma_{wt}(t) + \frac{\gamma}{T_w}\overline{\Delta}\Omega_l(t)
- \frac{\gamma}{J_T\eta}\frac{\overline{\Gamma_G}}{\overline{\Gamma_{wt}}}\overline{\Delta}\Gamma_G(t) + \frac{2-\gamma}{T_w}e(t)$$
(14)

Formula (11) and (14) constitute the high-frequency sub-model of the conversion system, for this model and according to the theory above, $u(t) = \overline{\Delta\Gamma_G}$ is chose as the control input, $x(t) = \begin{bmatrix} \overline{\Delta\Omega_l} & \overline{\Delta\Gamma_{wt}} \end{bmatrix}^T$ is the state vector, $y(t) = \overline{\Delta\lambda}(t) = C(\rho(t))x(t)$ is defined to be the output vector, and the matrixes obtained by formula (14) are

$$A = \begin{bmatrix} 0 & 1/J_T \\ \gamma/T_w & \gamma/J_T - 1/T_w \end{bmatrix} , \qquad B = \begin{bmatrix} \frac{-1}{J_T} \overline{\Gamma_G} \\ \frac{-\gamma}{J_T} \overline{\Gamma_W} \\ \frac{-\gamma}{J_T} \overline{\Gamma_G} \\ \frac{-\gamma}{J_T} \overline{\Gamma_W} \end{bmatrix}$$
$$L = \begin{bmatrix} 0 & (2-\gamma)/T_w \end{bmatrix}^T , \qquad C = \begin{bmatrix} \frac{2}{2-\gamma} & -\frac{1}{2-\gamma} \end{bmatrix}$$

Use the LMI toolbox to describe the matrix of the theorem 1 to obtain the controller K.

4. ONLINE SIMULATION AND RESULTS ANALYSIS

According to the Figure 1 and the analysis above, the general structure diagram of the direct-driven permanent magnet synchronous wind power system based on LPV is shown in Figure2, and the online experiment is done by dSPACE. dSPACE system is a development and testing working platform based on MATLAB/Simulink in real-time environment, it can be connected with MATLAB/Simulink seamlessly, and can realize real-time control and modify for the control system, so it is much easier and overcomes some inconvenience of out-line simulation.



Figure 2: Gain Scheduling Control Structure Based on LPV

In MATLAB simulation environment, find the solution of matrix in theorem 1 with LMI and Simulink toolbox, and build the general simulation diagram of the system, then download the simulation to the dSPACE to do the real-time simulation experiment. The parameters of the experiment are shown in Table 1.

Table 1:Experiment Parameters			
Name	Value	Name	Value
R	2.5 m	ρ	1.25kg/m ³
T_w	21.4286s	η	0.95
J_{T}	0.5632 kg*m ²	C _{pmax}	0.476
$\Gamma_{G \max}$	40Nm	λ_{opt}	7

The experiment results of power factor of the wind turbine C_p and tip speed ratio λ (lam) are shown in Figure 3 and Figure 4.



Figure 3: Power Factor



Figure 4: Tip Ratio

From Figure 3, it is easy to see that the value of C_p is stable and very closed to the maximum value 0.476; and the Figure 4 shows that the accuracy of tip speed ratio tracking the best value is high, and the robustness of the system is good, so the controller can capture the wind energy as much as possible, and the oscillation is small, solve the contradictions between the wind energy capturing and big oscillation. The experiment results show the effectiveness and advantages of this control method.

5. CONCLUSION

The situation discussed in this paper is below the rated wind speed of the direct-driven permanent magnetic synchronous wind power system, we need to capture the maximum wind energy and to ensure the smaller mechanical vibration, while increasing the model precision, firstly we build the basic model of the system, then for the high-frequency part, according to the LPV theory to linear the part and design the LPV controller, with PI control of the low-frequency part, the torque can be controlled well. The experiment results based on the dSPACE show that the control method of this paper can fulfill the control objective and efficiently improve the performance. The research of this paper has broad application prospects in direct-driven permanent magnetic synchronous wind power system.

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